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DOI:
10.1177/0954409719830184

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Document Version
Peer reviewed version

Citation for published version (Harvard):
Faramehr, S, Hemida, H & Fujiyama, T 2019, 'Evaluation of the impact of urban water systems on railways: the scenario of track flooding caused by a water main burst', *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*. https://doi.org/10.1177/0954409719830184

Link to publication on Research at Birmingham portal

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Faramehr, S., Hemida, H., & Fujiyama, T. (2019). Evaluation of the impact of urban water systems on railways: The scenario of track flooding caused by a water main burst. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit. https://doi.org/10.1177/0954409719830184 © IMechE 2019

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Evaluation of the impact of urban water systems on railways: the scenario of track flooding caused by a water main burst

Samane Faramehr, Hassan Hemida, Taku Fujiyama

Abstract

Failures and disruption scenarios can reveal inherent but little known dependencies that exist between technical infrastructure systems. Whereas the dependencies between infrastructures in their normal state of operation are usually obvious and mutually correlated, interdependencies when systems are disrupted show a great deal of variety, depending on the specific scenario. The literature reveals the lack of a proper tool that can evaluate and quantify the scenario of track flooding caused by a water main burst, a cross-sectoral failure that can impact the operation of two urban infrastructure systems: the railways and the water supply. This work presents an approach to investigate the impact of urban water systems on railways and applies it to the case study of the Thameslink railway and Thames Water assets in London. The developed tool can be integrated into city level water supply GIS systems to facilitate the understanding of external risks (transport disruption) caused by an internal failure (water main bursts). Also the results can help railway system operators facilitate the decision making process in terms of drainage policy and maintenance activities.

Introduction

Critical technical infrastructures, sometimes referred to as large-scale spatially distributed systems, with high degrees of complexity provide essential services for the society. Different infrastructures (i.e., energy, transport, water, waste and information and communication technology) have developed over centuries, being planned and implemented individually. These systems are mostly managed in isolation from one another, ignoring the dependencies, linkages and feedback from other infrastructures [1]. However, infrastructure systems are actually highly interconnected and interdependent and hence what happens to one system can directly or indirectly affect other systems. Infrastructures interact in complex ways through direct connectivity, strategies and functions or spatial proximities [2]. Dependencies need to be understood properly for the normal state of operation of systems as well as for their vulnerabilities. Disturbances in one infrastructure can cross over to other dependent infrastructures and possibly can return to the infrastructure where the disturbances originated. Potential cascading effects and risk analysis in interdependent infrastructures has been the subject of many studies (e.g. [3], [4], [5], [6] and [7]) in different geographic and time scales. Indeed, the silo approach of managing infrastructures within traditional boundaries of one infrastructure system and ignoring collaboration with other infrastructure operators fails to consider such cross-sectoral risk scenarios.

In many cases interdependent risks at a technical level have been neglected and hence not well investigated due to one (or all) of the following challenges:

- Infrastructure Sectors have different identification and prioritizations of risks according to their particular goals and hence stakeholders have different concerns.
- Relevant asset data are lost or insufficient (especially in highly complex systems)
- The impacts on one (or more) of the systems may be indirect (e.g. the operation of the systems itself is not disturbed). Additionally, although the scenario can have a significant impact (consequence) on systems, its likelihood is usually low.
- The origin and the flow of failures within interdependent infrastructures may not be visible or reported.

A prime example of such a risk at operation level is the scenario of track flooding in a city. A burst in a major water main adjacent to a railway track can cause flooding that disturbs the operation of both of the technical infrastructures (the railways and the water supply systems). The consequences of such incidents can vary from a few minutes to days of train delays, interruption to water supplies, and financial and social losses for the railway and water supply companies. In urban areas, in addition to pluvial and fluvial flooding, two other types of flood hazard sources have been recognised: burst water mains and direct connections (sewers). The limited infiltration and drainage capacity in urban areas and the highly complex interaction of infrastructure systems (utilities, water supply, transport etc.) together with the population density represent a genuine challenge. Floods pose a considerable risk to the assets and the operation of technical infrastructures. The railways assets and especially track and trackside assets are liable to be disrupted by undrained water in flood-prone areas such as at the foot of cuttings and natural slopes, over and under bridges and inside tunnels. The behaviour of the flood may vary depending on the source(s) of flooding and the physical attributes of the flooded premise(s) (e.g. railway track, road, underground tunnels and basements) in urban areas.

On the other hand, while an urban railway system transports passengers according to a time table, an urban water system is responsible for both a consistent water supply to public and waste water management. In a normal operating condition it is expected that none of the systems will disrupt the others. However, in the case of risk scenarios, such as track flooding caused by a water main burst, the operation of both systems may be disrupted. Although flooding is considered as a risk for the both geographically proximate systems, its impact on the operation of a railways is more direct. This is due to the fact that the water supply system may still be able to provide water to customers (and hence meet the system's purpose) while the flooded railway system cannot operate normally before the necessary handling has been implemented. Furthermore, flood risk considerations usually ignore a burst water main as a flood source. This is because burst water mains are very difficult to predict and generally occur randomly, most likely as a result of infrastructure failure. Although burst water mains in general have been investigated before ([8] and [9]), the particular consequences of flooding caused by a burst for a railway system have been largely ignored in academic literature. London Underground developed a GIS-based flood risk analysis to include all sources of urban flooding (including connections and mains) [10]. The risk analysis found that of all flood sources, water main bursts contribute to the highest flood risk for Transport for London (TfL) assets.

This research has developed a tool that can evaluate the scenario of track flooding caused by a water main burst and quantify the dependency of the operation of a railway system on such flooding. The model and results can aid the prioritisation of investments and risks as well as enable the optimisation of maintenance activities for both railways and water companies by providing a quantified measure of a dependency scenario.

Note that this study aimed neither at understanding the underlying factors of trunk main failure nor its likelihood and risk. Rather it aimed at understanding the impacts such bursts have on railways infrastructure and operation. As the term "interdependency" indicates, linkages and impacts between infrastructures may be bidirectional [1]. Therefore, the scenarios of the disruption of a water supply system caused by railway operation and maintenance also require attention. Examples of this include the deterioration and damage of water assets due to maintenance activities such as track tamping or stray current from tracks of electrified railway lines. However, because there need to be different methods for investigation of such impacts of railway systems on water systems, this study focuses only on the direct impacts of main burst induced flooding on railways operation.

Understanding the dependency scenario

In the first place, it is necessary to understand the dependency scenario under consideration so that a suitable tool can be developed. This study used stakeholder engagement to realize the scenario of track flooding caused by a water main burst and its importance for infrastructure managers. Subsequently, it carried out a case study to investigate a real world example and developed a generic tool using hydraulic analysis and numerical simulation.

Thames Water Utilities Limited (TWUL) is responsible for supplying clean water and treating waste water in Greater London and the South of England. TWUL manages approximately 30,000 km of water mains, of which 17,000 km are trunk mains [8]. Trunk mains are large pipes (18” diameter or larger) which carry a significant volume of water at high pressure. Towards the end of 2016 Thames Water suffered eight separate bursts on their trunk main network. These caused significant damage to infrastructures and businesses and temporary losses of water supply [11]. Regarding bursts adjacent to railways, in January 2015 water from a burst water main stayed on the track around Farringdon (Thameslink) and led to track flooding, which stopped all train operation for 2 days [12]. London Underground experienced a similar incident in June 2012, in which water from a burst water main went into the Central Line’s tunnel and stopped the line for 2 days [13].

Generally, if track flooding occurs, drivers must report any floodwater with the potential to affect the passage of trains to the signaller, who in turn must report it immediately to operations control. As soon as the flooding source is detected and it is reported to the water supply company, a decision needs to be made to stop the water supply. Because the size of the trunk mains are large and the water runs under high pressure, the flow may not stop until up to 3-5 hours after switching off the supply.

Network Rail is the owner and manager of most of the railways infrastructure in England, Scotland and Wales that is also responsible for maintaining more than 20,000 miles of track including Thameslink railway, a mainline route running through London. When the railway track is located lower than the surrounding area (e.g. in cuttings and tunnels) it is prone to flooding. Flooding is specific in urban areas in the fact that there is a lack of sufficient drainage in cities. In London, the railway drainage is directly connected to public sewer which represents a unique challenge. The railway rule book sets out standard procedures for the operation of trains through flood water:

1. If the water depth is above sleeper level, but below the bottom of the railhead, then trains can proceed at line speed.
2. If the water depth is above the bottom of the railhead, but below the top of the railhead, trains may proceed at 5 mph.
3. If the water depth is above the top of the railhead, trains may only proceed if given express permission to do so by Operations [14]

Major London railway infrastructure operators, Network Rail and London Underground, as well as the water supply company TWUL agree that it is necessary to develop tools for better understanding of the shared risk of urban flooding. This requires improvement in communication, asset information and quantified analyses of risks.

In order to evaluate the disruption scenario, data and information were collected from relevant stakeholders for the case study area. The data includes; GIS data of trunk mains, track features (e.g. tunnels and bridges), signalling equipment and gradient of railway line in the case study area. Additionally, policies on the operation of vehicles through floodwater [14] and the general railways standards regarding the track and drainage [15] were used. Furthermore, further data (e.g. water pressure in trunk mains, the duration of flooding, etc.) was collected in workshops and interviews because the values of such parameters were not available publicly.

Numerical simulation using MATLAB has been carried out in order to model the movement of water from the burst onto the track. The track area has been discretized into elements through which flood water flows in and flows out. The number of cells varies based on the scenarios in which the distance between the flood source and flood water accumulation point varies in order to optimize the fidelity and resolution of results. The point which flood water moves towards and at which it accumulates along the railway line is called “the lowest point”. The topographic map of London [16] shows a rise in elevation from central London towards the North West where the railway line extends. Therefore, in general it is true to assume that in a case of flooding the water movement tends to be in the direction of the lower elevation (e.g. towards Moorgate in central London). However, to be more specific, the longitudinal elevation of the track is not constant for the entire line and hence the tool considers different angels of inclination along the flooded track. In order to limit the scope of the work the transverse elevation of the track has not been considered for the study. Because, only the mains located in close proximity to the railway are considered for the modelling, it is assumed that the effect of the transverse elevation would be negligible for the water movement. The case study focuses on sections of Thameslink (North of Farringdon) and Midland Main Line within London where railway track is surrounded by trunk mains with sizes between 18” and 102”.

Based on equation (1), the water discharge from the burst depends mainly on the area of the orifice and the pressure difference, which are both assumed to the equal in all trunk mains in the network [17].

$$Q = C_f A_o \sqrt{\frac{2\Delta P}{\rho}} \qquad (1)$$

Here, C_f is the coefficient of discharge, A_o is the area of the orifice, ΔP is pressure drop and ρ is fluid density.

There is no information available about the area/size of the bursts. Therefore, for the mains in the area (diameter between 18” and 102”) the orifices in the pipes were assumed to be circular with a maximum of 0.15 m in diameter. Based on TWUL, the pressure drop almost equals 215600Pa and C_f (the coefficient of discharge) is assumed to have a maximum of 0.9. Thus, a reasonable range of burst discharge (between $0m^3$/s and 0.2 m^3/s) is assumed for the analysis. This discharge has been assumed as the initial discharge onto the sloped track over and through which the water moves towards the lowest point. The hydraulic calculation of the flow down the slope was based on the Manning equation (2), which is used for the calculation of flow variables (including the depth/height of water at the lowest point and flow velocity) and it includes the slope of the open channel (gradient of the track in this case) as a variable. As a broad assumption, the flood flow was considered as steady uniform flow in an open channel running for 3 hours. Although in many cases the orifice size will be much smaller and the burst running time will be shorter, the broad assumptions represent a worst case scenario for this analysis.

$$\frac{Q}{A} = U = \frac{1}{n} R^{2/3} S^{1/2} \quad (2)$$

Here, $A(\mathrm{m}^2)$ is the area of the open channel, n is the Gauckler–Manning coefficient, R (m) is the hydraulic radium and S is the slope of the open channel [17].

The ballast has been taken as a porous medium through which the flow passes cell by cell and is absorbed by sublayers. The local drainage systems, about which no asset data was available, have been taken as either present or absent (representing blocked drainages). Furthermore, ignoring the signalling assets required for railway control and operation, according to the rule book [14], the flooding criteria for track mainly depends on the rail profile. Eventually, regarding the flooding criteria, four values of water depth or H were assumed as H=0 (the beginning of the flooding), H=0.1 m (the water depth is above sleeper level, but below the bottom of the railhead), H=0.15 m (the water depth is above the bottom of the railhead but below the top of the railhead) and H=0.25 m (the water depth is above the top of the railhead). The values are based on the standard British Steel flat rail profiles [18].

It is important to acknowledge that in some cases, the responses of companies to disruptions may deviate from the actual contingency plan due to conflicts of interest. For instance, although flooding is considered as a risk for both (and eventually all) geographically proximate systems, its impact on the operation of railway system is more direct. This is due the fact that the water supply system may still be able to provide water for customers (and hence meet the system's purpose) after a burst while, the flooded railway system cannot operate normally. To stop the water running out of the burst, the water supply (for customers) needs to be stopped within the premises of the incident and this may be considered a larger risk for the water company than flooding a proximate infrastructure (in this case railways). However, from the viewpoint of a railway infrastructure manager, the leakage must stop as quickly as possible, hence their customers (train operating companies) can run the trains. Therefore, from a modelling perspective parameters such as time of flow running in the premises of the track may be adjusted accordingly. This indicates that the concerns and motivations of relevant stakeholders need to be captured for developing modelling and simulation tools which facilitate investigating little known dependency scenarios.

Validation of the numerical model

To validate the developed numerical model, we have conducted a small scale experiment which used a mobile bed model tank. The measurements in the experiment were compared to the outputs of the developed model run for the same conditions. The dimensions of the bed are 600mm width and 2000m length. The device was flat simulating a zero or a very small gradient. These settings were chosen due to the dimensions of the bed. Two types of granular material were used, namely sand and gravel, to collect the results. The permeability (porosity) of both granular materials was measured before setting up the scaled track bed and running the test. Table 1 shows the variables and their values in the experiment.

Table 1 Variables in the track flooding experiment

Variable	Value in the experiment	Description
L	Sand: 2m Gravel: 2m	The length of the mobile bed simulating the distance between the burst and the lowest point
b	Sand: 0.6m Gravel: 0.6m	The width of the mobile bed simulating the width of the track
d	Sand: 0.078m Gravel: 0.03m	The depth of granular material on the bed
Q	Sand: 0.00256 $\frac{m^3}{s}$ Gravel: 0.000671$\frac{m^3}{s}$	The steady flow of the water from the tank moving along the bed
∅	Sand: 0.35 Gravel: 0.44	The porosity of the granular material simulating the ballast porosity
S	Sand: 0.001 Gravel: 0.001	The gradient of the bed simulating a flat gradient

n	Sand: 0.015 Gravel: 0.025	Manning coefficient

Next, the experiment was run to collect the results for both sand and gravel using two different flows of 0.00256 $\frac{m^3}{s}$ (for sand) and 0.000671$\frac{m^3}{s}$ (for gravel) (Figure 1 and Figure 2). The steady flow continued until the water reached the end of the granular bed and the depth of the flow became constant along the bed (Figure 3 and Figure 4).

Figure 1 Water movement along the sand bed

Figure 2 Water movement along the gravel bed

Figure 3 Water accumulated on top of the sand bed

Figure 4 Water accumulated on top of the gravel bed

The main collected data included; the distance of the front of the water from the source (“x” in metres) and the time it takes for the front of the flow to travel the distance (“t” in seconds) as well as the depth/height of the collected water above the granular bed (“h” in metres) which are the main parameters representing the flow behaviour. Table 2 compares the two sets of output data from the experiment and the numerical model. As the two sets of results closely match (considering experimental uncertainties), the developed numerical model is validated and could be used for simulation of flooding on railway tracks.

Table 2 Comparison of the output from laboratory experiment and developed numerical model

Output	Value from the experiment	Value from the developed numerical model
Time (t)	Sand: 15 s Gravel: 25 s	Sand: 14.9 ± 0.5 s Gravel: 24.7 ± 0.5 s
Steady depth/height of water (h)	Sand: 0.025 m Gravel: 0.015 m	Sand: 0.024 ± 0.050 m Gravel: 0.014 ± 0.050 m

Parametric study

To carry out a parametric study, an appreciation of the roles of the different elements is required. Since the tool is generic, all values can be altered by the user on an individual burst by burst basis to make the result more site specific. It is necessary to define the appropriate metrics for investigating interdependency. The metric is supposed to relate two systems in connection with the same risk scenario. Also since this risk scenario has an impact on the operation of the railway the metric is required to reflect that impact. Therefore, considering the standard procedures for the operation of trains through flood water and the discharge from a burst, "time for track flooding" has been chosen as the dependency metric. This metric indicates the time length for water from a burst to flood a track.

Figure 5 indicates that when water flows 0.055 m^3/s from a burst in a trunk main adjacent to a railway track, it takes 53 minutes for the water to accumulate above the top of the railhead (H=0.25 m) at the lowest point of the track. It clearly takes shorter time for the water to be accumulated below the top of the railhead at different depth/height (e.g. H=0 m, H=0.1 m, H=0.15 m and H=0.25 m).

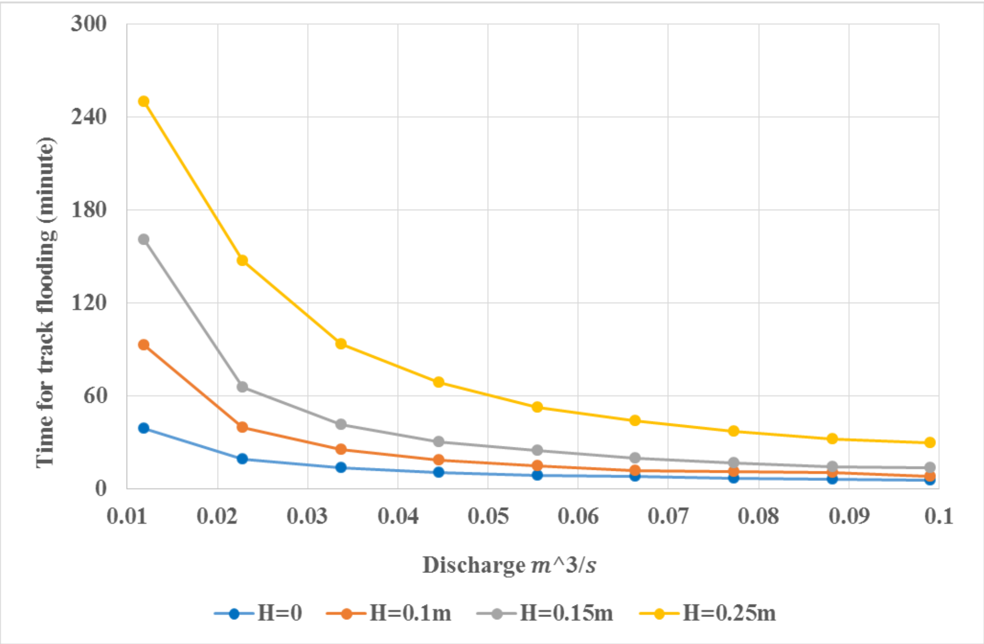

Figure 5 Time for different track flooding criteria. Here, the distance between the burst and the lowest point is 120m, the gradient of the track is 1/33 on the flooding side and 1/333 on the other side. A drainage of 0.002m^3⁄s capacity exists along the track at every 40m.

Note that parameters such as; the distance between the burst and the lowest point of the track, the gradient of the track, as well as the ballast porosity and the drainage arrangement can significantly affect the time length for track flooding.

Figure 6 shows the effect of the distance between the burst and the lowest point of the track on the length of time for the track to be flooded to the top of the railhead (H=0.25m). Although it clearly takes less time for the track to be flooded when the burst occurs nearer the lowest point, when the discharge is large (>0.1m^3/s) no significant difference is observed between the time lengths for track flooding. This emphasized on the effect of the size of the burst on track flooding (Figure 7). For orifice sizes larger than 0.1m diameter, it takes less than 15 minutes to flood the lowest point of a track when the distance between the burst and the lowest point varies between 100m and 500m.

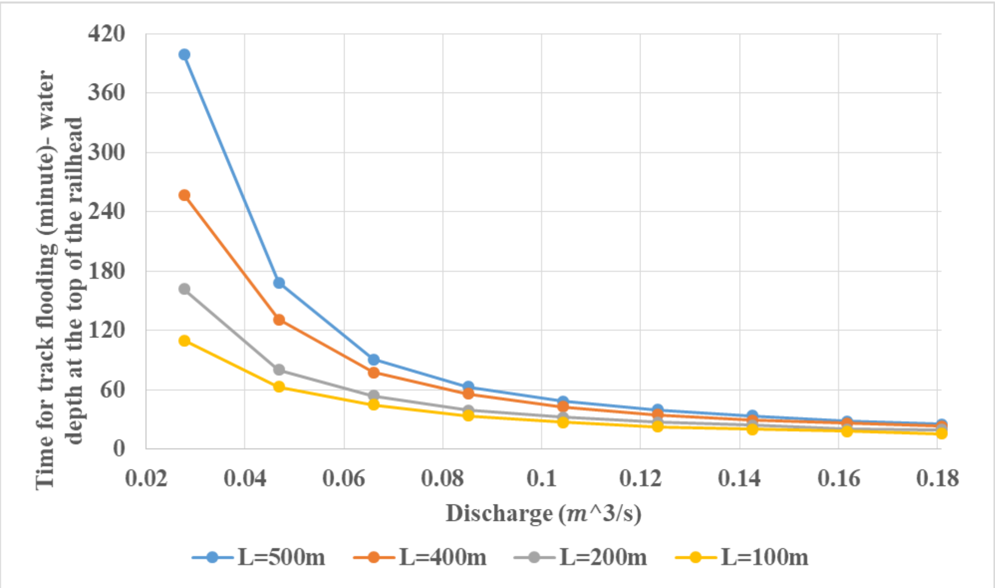

Figure 6 The effect of distance (L) between burst main and lowest point of the track on time for track flooding (gradients varying). For L=500m gradients at the side of the flooding are 1/89, 1/56 and 1/66. For L=400m gradients at the side of the flooding are 1/56 and 1/66, and for L=200m and L=100m the gradient at the side of the flooding is 1/66. A drainage of 0.002m^3⁄s capacity exists along the track at every 40m.

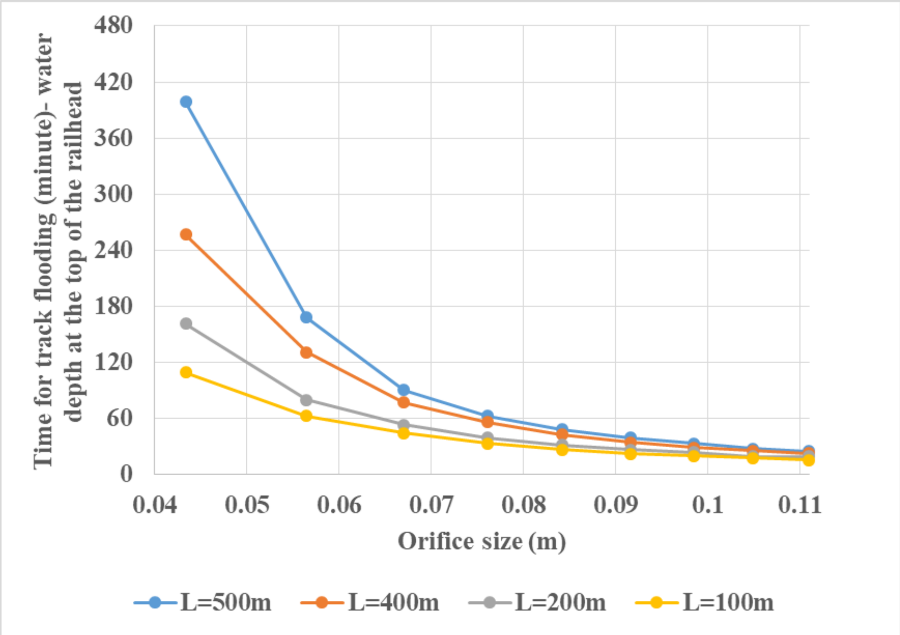

Figure 7 Time for track flooding for different orifice size. For L=500m gradients at the side of the flooding are 1/89, 1/56 and 1/66. For L=400m gradients at the side of the flooding are 1/56 and 1/66, and for L=200m and L=100m the gradient at the side of the flooding is 1/66. A drainage of 0.002m^3⁄s capacity exists along the track at every 40m.

Furthermore, it is necessary to investigate the effect of natural drainage (drainage through ballast) on the flooding. Ballast track, a granular material, is still the most common railway load bearing structure. The thickness of the ballast layer is usually 0.25-0.3m. The properties of new ballast including its shear strength and permeability are different from those of older ballast. These properties change progressively because of breakage, erosion and fouling. Fouling reduces the permeability of ballast layer and therefore, decreases natural drainage [19].

The permeability of the ballast has been incorporated into the model using a “porosity” parameter, which is defined as the fraction of the volume of voids over the total volume of the ballast. It is assumed that the porosity is uniform all over the track. Figure 8 shows the effect of the porosity of the ballast on the time for track flooding when the distance between the burst and the lowest point is 120m. Obviously when the ballast is old (the porosity/ permeability is decreased) it takes shorter time for the track to be flooded. Again, the effect of the discharge (and hence of the burst size) must not be ignored. For a larger discharge little difference was obtained in the curves and the track may be flooded in less than an hour’s time.

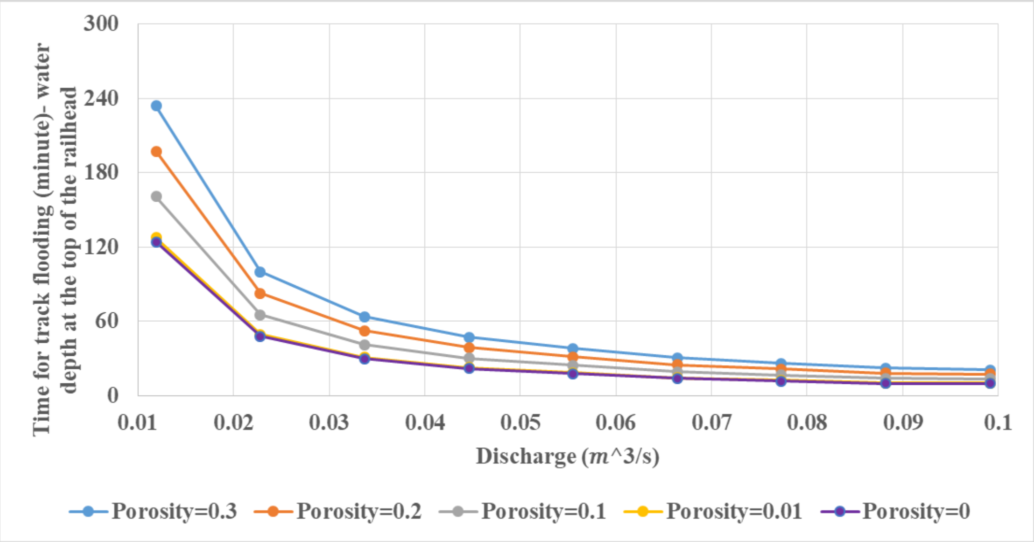

Figure 8 Time for track flooding for different ballast porosity. The distance between the burst and the lowest point is 120m, the gradient of the track is 1/33 on the flooding side and 1/333 on the other side. A drainage of 0.002m^3⁄s capacity exists along the track at every 40m.

This shows the importance of the drainage mechanism under the track. In many actual cases the railway drainage is blocked or abandoned and cannot be maintained because of short track possession time available for planned engineering works especially in urban areas where lines are congested. Furthermore, some railway systems have little or no understanding of their drainage asset inventory because their railway network is complex in terms of its diversity and dispersion. Also in the past there were examples of an absence drainage in the case study area.

Figure 9 shows the effect of the drainage capacity at the site when a burst occurs in the same case study mentioned above. The results show that discharges greater than 0.04 m^3/s are large enough to flood the track regardless of the capacity of the drainage.

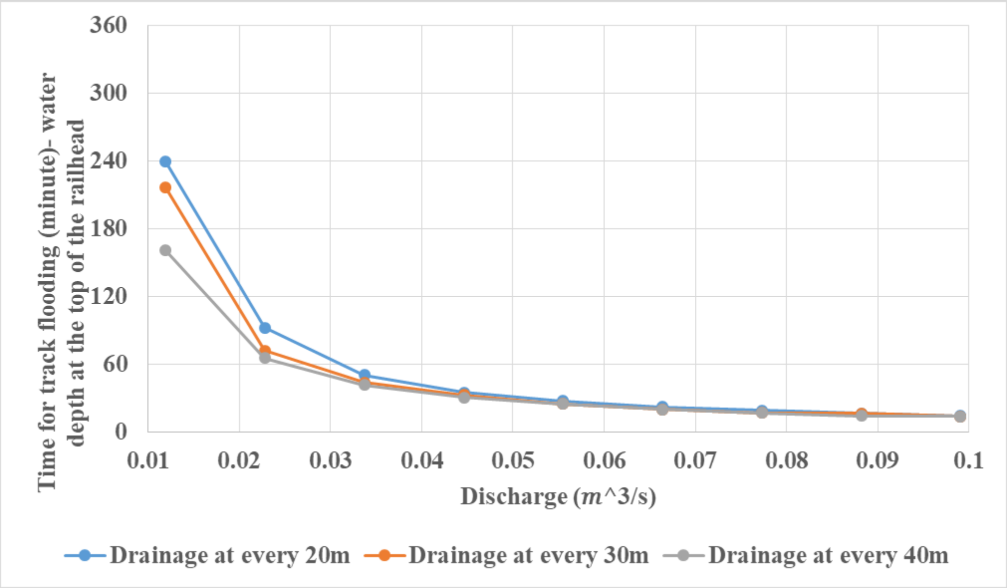

Figure 9 Time for track flooding for different ballast porosity. The distance between the burst and the lowest point is 120m, the gradient of the track is 1/33 on the flooding side and 1/333 on the other side. A drainage of 0.002m^3⁄s capacity exists along the track at every 40m.

Last but not least, although the routing and railway gradient are usually the concerns of the traction of a railway, the effect of the gradient on the water movement cannot be ignored. Figure 10 shows the effect of the railway gradient on the time length for track flooding. When the railway is almost flat (gradient equals 1/1000) the time for track flooding is significantly longer.

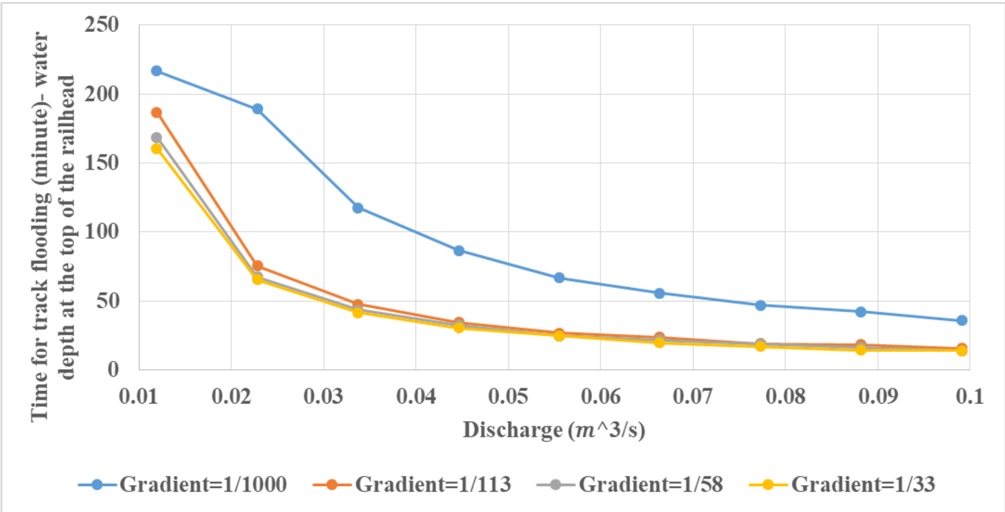

Figure 10 Time for track flooding for different ballast porosity. The distance between the burst and the lowest point is 120m. A drainage of 0.002m^3⁄s capacity exists along the track at every 40m.

Conclusion

Considering the convergent future challenges such as climate change and demographic changes, we can no longer wait until failures reveal the dependencies that exist between infrastructures. Different models and tools which look at the effect of interdependencies from different viewpoints are necessary for a comprehensive understanding of this topic. However, modelling and analysis of complex systems and in particular modelling and analysis of infrastructure dependencies have great challenges and the knowledge in this field is still in early stage. Hence, in the first place less evident dependencies that may appear as cross-sectoral risks should be identified by studying past examples and stakeholder engagement. Later, considering concerns and motivations of relevant stakeholders, modelling and simulation tools should be developed to provide further knowledge about the particular dependency.

This work developed an evaluation tool to facilitate characterisation of a specific dependency that exist between two infrastructure systems namely; urban railway and trunk main network at operation level. It first identified the general disruption scenario of risk that creates a dependency which is not evident while urban systems operate normally. The study later quantified such dependency by introducing “time for track flooding due to burst discharge” as a metric and carried out a parametric study. The results showed that parameters such as the distance between the burst and the lowest point of the track, the gradient of the flooded track, the permeability of the ballast and the capacity of the drainage affect the time for track flooding and hence the operation of the railway. However, the discharge from trunk mains (source of the flood) plays a major role in impacting railway operation.

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